Constraints on Ultracompact Minihalos from Extragalactic γ-ray Background

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Abstract. It has been proposed that ultracompact minihalos (UCMHs) might be formed in earlier epoch. If dark matter is in the form of Weakly Interacting Massive Particles (WIMPs), UCMHs can be treated as the γ-ray sources because of the dark matter annihilation within them. In this paper, we investigate the contributions of UCMHs formed during three phase transitions (electroweak symmetry breaking, QCD confinement and e^+e^- annihilation) to the extragalactic γ-ray background. Moreover, we use the Fermi-LAT observation data of the extragalactic γ-ray background to get the constraints on the current abundance of UCMHs produced during phase transitions. We also compare these results with those obtained from Cosmic Microwave Background (CMB) observations finding that the constraints from the Fermi-LAT are more stringent than CMB.

Contents

1 Introduction

It has been known that the present structures of cosmology originate from the density perturbations ($\delta \sim 10^{-5}$) in earlier epoch. Recently, the authors of [1] have proposed that a new class of dark matter structure, ultracompact minihalos (UCMHs) would be formed if the density perturbations are between 3×10^{-4} and 0.3 which are not enough to produce the primordial black holes (PBHs). Although within the conventional cases the density perturbations are not larger enough to form these objects, they could be enhanced through the inflation potential or during the phase transitions in the early Universe [2]. On the other hand, if dark matter is in the form of Weakly Interacting Massive Particles (WIMPs), UCMHs would become the sources of γ-ray due to the dark matter annihilation within them. In paper [3], the authors have investigated the integrated γ-ray flux of nearby UCMHs formed during three transitions: electroweak symmetry breaking (EW), QCD confinement and e^+e^- annihilation. They find that for the same mass fraction, the flux from UCMHs formed during e^+e^- within the 100pc would have been observed by EGRET or Fermi-LAT. The authors of [4] have obtained the constraints on the abundance of UCMHs using the point source sensitivity of $Fermi$ above 100 MeV from the neighborhood: $f_{UCMHs} \sim 10^{-7}$ for $M_{UCMHs} \sim 10^3 M_\odot$. The constraints on the UCMHs formed during e^+e^- annihilation using the WMAP-7 years data and the forcast for the Planck-3 are obtained by authors in [5, 6].

The extragalactic γ-ray background has been observed by $Fermi$ satellite [7] and its origination has not known exactly now. The main sources would be the usual, unresolved astrophysical objects, such as the Active Galactic Nuclei (AGN), normal galaxies and the clusters of galaxies [8, 9]. Other possible sources may be the dark matter annihilation [10–12]. In our paper, we consider the contributions of dark matter annihilation from UCMHs, and get the constraints on the current abundance of them using the $Fermi$ observations.

In addition, the annihilation of dark matter has an effect on the cosmological evolution [13] e.g. recombination and reionization. So the property of dark matter can be constrained by the CMB observations. UCMHs would have the similar effect because of their higher density, and the CMB data can give constraints on their nature. Here, we also use the CMB data to investigate the current abundance of UCMHs.

This paper is organized as following: we calculate the extragalactic γ-ray background from UCMHs in section II. In section III, we get the constraints on the current abundance of UCMHs using the $Fermi$ and CMB data, and we conclude in section IV.

2 Extragalactic γ-ray Background

2.1 Extragalactic γ-ray background from UCMHs

After the formation of UCMHs, they can accret the dark matter particles onto them by radial infall due to their higher density. The mass of UCMHs changes as [3]:

$$M_{\text{UCMHs}}(z) = \delta m \left(\frac{1 + z_{\text{eq}}}{1 + z} \right), \tag{2.1}$$

where the δm is the mass contained within a perturbation at the redshift of matter-radiation equality z_{eq}. Following [3], we adopt the value of $\delta m = 5.6 \times 10^{-19} M_\odot, 1.1 \times 10^{-9} M_\odot, 0.33 M_\odot$ for three phase transitions: EW, QCD and $e^+ e^-$.

The density profile of UCMHs is [3]:

$$\rho_{UCMHs}(r, z) = \frac{3 f_\chi M_{\text{UCMHs}}(z)}{16 \pi R_{\text{UCMHs}}(z)^{\frac{3}{4}} r^{\frac{9}{4}}}, \tag{2.2}$$

here $R_{\text{UCMHs}}(z) = 0.019 \left(\frac{1000}{z+1} \right) \left(\frac{M_{\text{UCMHs}}(z)}{M_\odot} \right)^{\frac{1}{3}}$ pc and $f_\chi = \frac{\Omega_{DM}}{\Omega_b + \Omega_{DM}} = 0.83$ [15] is the dark matter fraction. We accept the assumption that UCMHs stop growing at $z \approx 10$ because the structure formation process prevents further accretion after the redshift.

The diffuse extragalactic γ-ray flux from the annihilation of dark matter can be written as [12]:

$$\frac{d\phi_\gamma}{dE} = \frac{c}{4\pi} \int_0^{z_{up}} dz \frac{e^{-\tau(z, E_0)}}{H(z)} \int dM \frac{dn}{dM}(M, z) \frac{d\mathcal{N}_\gamma}{dE} \left(E_0 (1 + z), z \right) . \tag{2.3}$$

where $H(z) = H_0 \sqrt{\Omega_M (1 + z)^3 + \Omega_\Lambda}$. The upper limitation of integration $z_{up} = M_\chi / E_0 - 1$ [16]. τ is the optical depth, and three processes are considered for our purpose [17]: (i) photon-matter pair production, (ii) photon-photon scattering, (iii) photon-photon pair production. In fact, as shown in [17–19], the energy range $(10^8 eV \lesssim E \lesssim 10^{11} eV)$ and redshift of γ-ray $(0 \lesssim z \lesssim 1100)$ in which we are interest are not affected by the medium. It is corresponding to the 'Transparency window' of photons, and these photons will propogate freely almost. For the energy range of photons $E \lesssim 10^5 eV$ and $E \gtrsim 10^{11} eV$, there are stronger absorption by the medium during all redshift and dot not form the γ-ray background. dn/dM is the mass function. In our paper, we consider the monochromatic mass fuction for UCMHs, which means all of them have same mass [20]: $dn/dM(M, z) \sim \delta(M - M(t_i))$. We assume that the abundance of UCMHs is same everywhere and they do not merger with others. $d\mathcal{N}_\gamma / dE$ is the number of γ-rays from one of UCMHs per unit of time and energy:

$$\frac{d\mathcal{N}_\gamma}{dE}(E, z) = \frac{\langle \sigma v \rangle}{2} \frac{dN_\gamma(E)}{dE} B_f \int \left(\frac{\rho_{UCMHs}(r, z)}{M_\chi} \right)^2 d^3 r \tag{2.4}$$

$\langle \sigma v \rangle$ is the thermally cross section of dark matter and M_χ is the mass of dark matter. dN_γ / dE is the energy spectrum of the γ-ray from dark matter annihilation. Here, we only consider the prompt emission case and use the public code DarkSUSY [21] to calculate for different channels. In this work, we consider two typical channels $\tau^+ \tau^-$ and $b\bar{b}$. In Fig: 1, the annihilation spectrum of these two channels are shown.
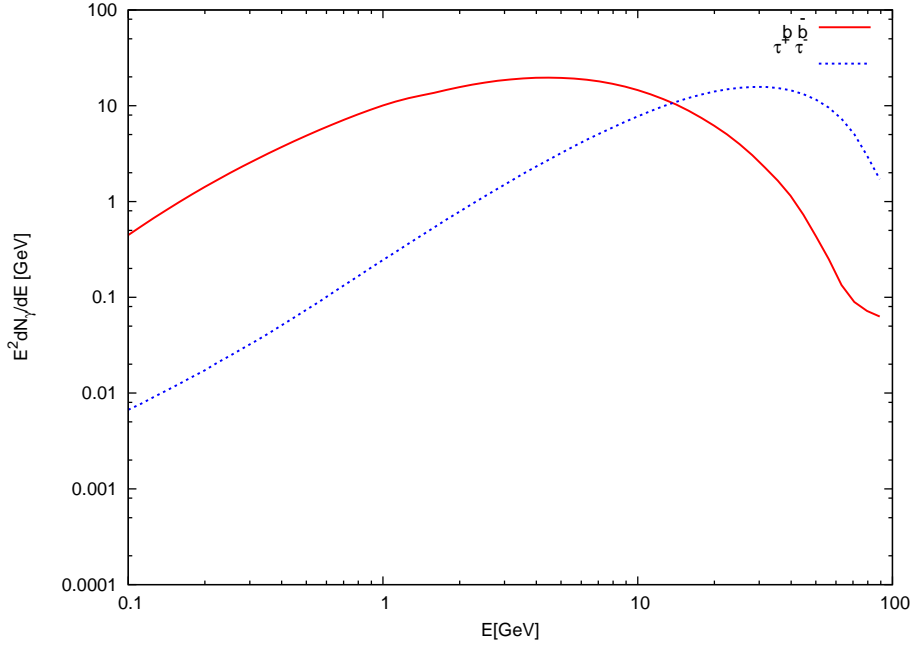
Figure 1. The annihilation channels ($\tau^+\tau^-$ and $b\bar{b}$) used in this work are shown. Here we have choosed the mass of dark matter $M_\chi = 100 GeV$.

B_f is the branch ratio of annihilation. In reality, different channels corresponds to different branching ratios. Here we consider each channel separately and take $B_f = 1$.

Base on these assumptions, we can write the differential energy spectrum of extragalactic γ-rays from UCMHs:

$$
\begin{aligned}
\left.\frac{d\phi_\gamma}{dE}\right|_{\text{UCMHs}} &= n_{UCMHs,0}\frac{c}{8\pi}\frac{\langle\sigma v\rangle}{M_\chi^2}\int dz \frac{(1+z)^3 e^{-\tau(E,z)}}{H(z)}\frac{dN_\gamma}{dE}(E,z)\int \rho_{UCMHs}^2(r,z)d^3r \\
&= \frac{f_{UCMHs,0}\rho_{c,0}}{M_{UCMHs,0}}\frac{c}{8\pi}\frac{\langle\sigma v\rangle}{M_\chi^2}\int_0^{z_{up}} dz \frac{(1+z)^3 e^{-\tau(E,z)}}{H(z)}\frac{dN_\gamma}{dE}(E,z)\int_{r_{cut}}^R \rho_{UCMHs}^2(r,z)d^3r \quad (2.5)
\end{aligned}
$$

$n_{UCMHs,0}$ is the number density now, $f_{UCMHs,0}$ is the current abundance of UCMHs and defined as $f_{UCMHs} = \rho_{UCMHs}/\rho_c$, $\rho_{c,0}$ is the critical density at present and $M_{UCMHs,0}$ is the mass of UCMHs at $z = 0$. Due to the annihilation of dark matter, there is the maximum density at present for a halo, so the r_{cut} can be defined as [22, 23]:

$$
\rho(r_{cut}) = \rho_{max} = \frac{M_\chi}{\langle\sigma v\rangle(t_0 - t_i)} \quad (2.6)
$$

where $t_0 = 13.7 Gyr$ is the age of universe, t_i is the time of UCMHs formation and we adopt $t_i(z_{eq}) = 77 kyr$ used by [4]. During the radiation dominated era, the growth of the UCMHs is very slow until the equality of matter and radiation. So we use the same value of t_i for three cases. Following [3, 4], we assume that the density is constant within r_{cut}, $\rho(r \leq r_{cut}) = \rho(r_{cut})$.

2.2 Extragalactic γ-ray background from halos

Besides the UCMHs, we include the extragalactic γ-ray background from halos, which is also produced by dark matter annihilation [12] [16]:

$$\frac{d\phi_\gamma}{dE}\bigg|_{\text{Halos}} = \frac{c}{8\pi}\frac{\rho_{c,0}^2\langle\sigma v\rangle}{M_\chi^2}\int_0^{z_{up}} dz(1+z)^3\frac{C(z)}{H(z)}\frac{dN_\gamma}{dE}(E,z)B_f e^{-\tau(E,z)} \tag{2.7}$$

here $C(z)$ is the 'clumping factor' relative to the homogeneous case [24], while the process of structure formation is considered.

$$\begin{aligned}
C(z) &= 1 + \frac{\Gamma_{halo}(z)}{\Gamma_{smooth}(z)} \\
&= 1 + \frac{(1+z)^3}{\bar{\rho}_{\text{DM}}^2(z)}\int dM\frac{dn}{dM}(M,z) \\
&\times \int \rho^2(r)4\pi r^2 dr
\end{aligned} \tag{2.8}$$

where Γ_s stand for the dark matter annihilation rate. dn/dM is the halos mass function and we use the Press-Schechters formalism [25]. On the other hand, it has been found that there are many substructures in dark matter halos [26]. These sub-halos can also enhance the dark matter annihilation rate. In our paper, we include these sub-halos, while neglect the contributions from the sub-sub-halos and use the smallest mass of them $\sim 10^{-6}M_\odot$ [26, 27]. We consider about $\sim 10\%$ halos mass within the sub-halos, use the power low form of mass function $\sim M^{-\beta}$ and adopt $\beta = 1.95$ [26]. So the total clumping factor of dark matter halos and sub-halos can be written as [24]:

$$C_{total} = 1 + (C_{halos} - 1) + (C_{subhalos} - 1) \tag{2.9}$$

In Fig. 2, for two typical channels $\tau^+\tau^-$, $b\bar{b}$, we show the extragalactic γ-ray background from UCMHs formed during EW, QCD, e^+e^- phase transitions, where the $Fermi$ data are from [7]. Here we have set $\langle\sigma v\rangle = 3.0\times10^{-26}cm^3s^{-1}$ and $M_\chi = 100GeV$. For the cosmological parameters we use the WMAP results [15]. For the case $f_{UCMHs} = 10^{-4}$, the flux approaches the $Fermi$ observation data especially for lower energy. The flux from those objects formed during the QCD and EW is same almost. We also show the γ-ray background from the halos. In Fig: 3, The γ-ray background from UCMHs for different redshift are shown. From there we can see that the main contributions come from $z \lesssim 200$.

3 Constraints on the current abundance of UCMHs

The production of dark matter annihilation would be standard particles, such as photons, electrons and positrons. These particles have interaction with the cosmological medium. So the processes of recombination and reionization can be influenced by the dark matter annihilation [13]. It is similar for UCMHs because of their higher density which can cause larger annihilation rate. The annihilation rate of UCMHs can be written as:
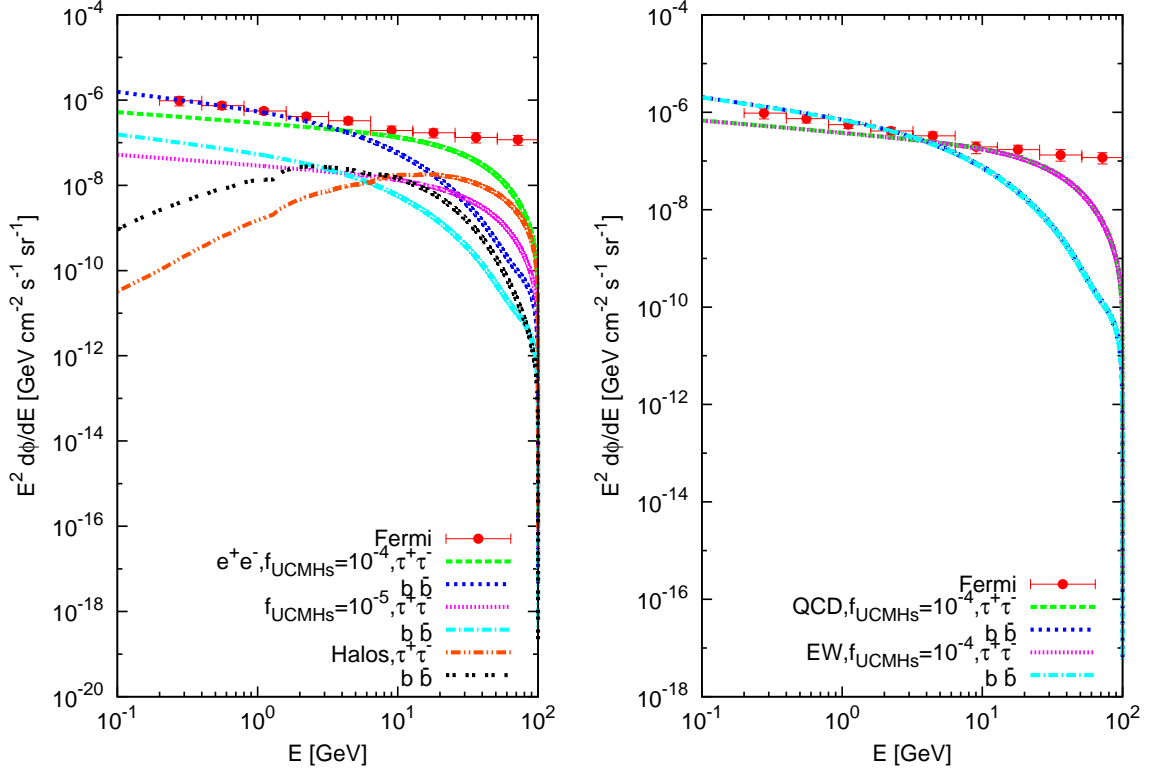
Figure 2. The extragalactic γ-ray background from UCMHs for different phase transitions, channels and current abundance. The contributions of halos are also shown. Here we have set $\langle\sigma v\rangle = 3 \times 10^{-26} cm^3 s^{-1}$ and $M_\chi = 100 GeV$, and for the other cosmological parameters we use the WMAP results [15]. The *Fermi* data are obtained from [7].

$$\Gamma = n_{UCMHs}\Gamma' = n_{UCMHs}\frac{\langle\sigma v\rangle}{M_\chi^2}\int 4\pi r^2 \rho^2(r,z)\mathrm{d}r$$

$$= \frac{\rho_{UCMHs,0}}{M_{UCMHs,0}}(1+z)^3\frac{\langle\sigma v\rangle}{M_\chi^2}\int 4\pi r^2 \rho^2(r,z)\mathrm{d}r$$

$$= \frac{f_{UCMHs,0}\rho_{c,0}}{M_{UCMHs,0}}(1+z)^3\frac{\langle\sigma v\rangle}{M_\chi^2}\int 4\pi r^2 \rho^2(r,z)\mathrm{d}r. \tag{3.1}$$

here Γ' is the annihilation rate within one of UCMHs and Γ is the annihilation rate per unit volume of UCMHs.

Considering the dark matter annihilation, the evolution of ionization fraction x_e can be written as [13, 14, 19]:

$$(1+z)\frac{dx_e}{dz} = \frac{1}{H(z)}[R_s(z) - I_s(z) - I_\chi(z)] \tag{3.2}$$

where R_s is the standard recombination rate, I_s is the ionization rate by standard sources, I_χ is the ionization rate sourced by dark matter which is given as [13]:

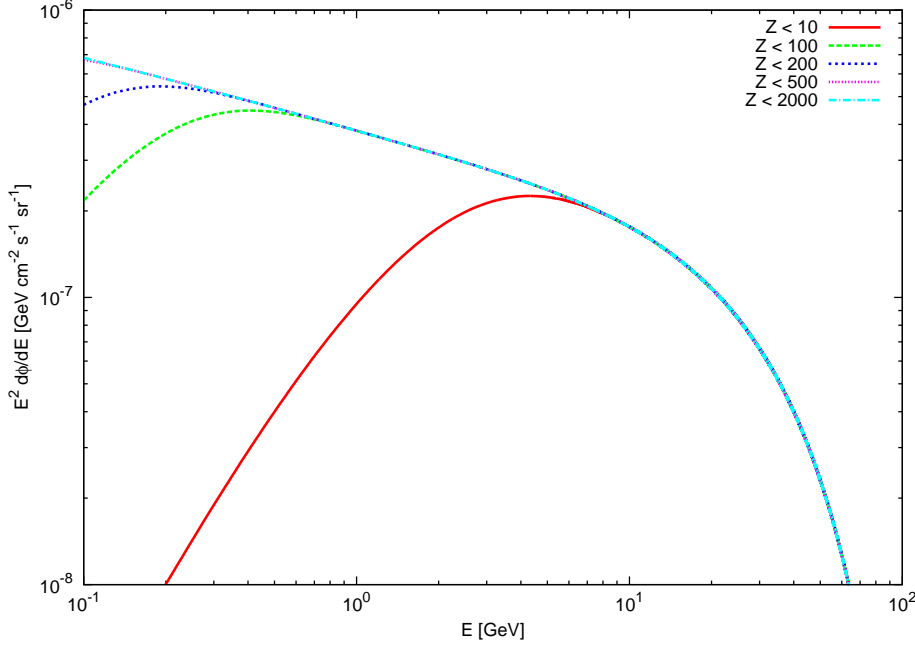$$I_\chi = \chi_i f\frac{2m_\chi c^2}{n_b E_b}\Gamma_{total} \tag{3.3}$$

Figure 3. The extragalactic γ-ray background from UCMHs formed during the e^+e^- annihilation for different redshift ranges, where the $\tau^+\tau^-$ channel is shown. Here we have set $f_{UCMHs} = 10^{-4}$, $\langle\sigma v\rangle = 3 \times 10^{-26}cm^3s^{-1}$ and $M_\chi = 100GeV$, and for the other cosmological parameters we use the WMAP results [15].

where n_b is the baryon number density and the $E_b = 13.6eV$ is the ionization energy. Γ_{total} is the total dark matter annihilation rate including the UCMHs and halos. f that depends on the redshift and the production of dark matter annihilation [28] is the released energy fraction depositing in the baryonic gas during the annihilation. In our paper, we assume that the total energy released by the annihilation is deposited, which means $f = 1$. χ_i is the energy fraction which ionizes the baryonic gas and we accept the form given by [19]:

$$\chi_i = (1 - x_e)/3 \tag{3.4}$$

here x_e is the fraction of free electrons.

We have modified the public code CAMB [29] and COSMOMC [30] in order to include the effect of UCMHs, halos and get the constraints on the parameters. We use the CMB data including seven years WMAP data [15], and the data from ACBAR [31], Boomerang [32], CBI [33] and VSA [34] experiments. We consider 6 cosmological parameters: $\Omega_b h^2, \Omega_d h^2, \theta, \tau, n_s, A_s$, where $\Omega_b h^2$ and $\Omega_d h^2$ are the density of baryon and dark matter, θ is the ratio of the sound horizon at recombination to its angular diameter distance multiplied by 100, τ is the optical depth, n_s and A_s are the spectral index and amplitude of the primordial density perturbation power spectrum. We fix the value of $\langle\sigma v\rangle = 3\times 10^{-26}cm^3s^{-1}$ and treat the current abundance of UCMHs (f_{UCMHs}) and the mass of dark matter (M_χ) as the free parameters. As it has been shown that the contributions of UCMHs formed during three phase transitions are same almost, so here we consider the e^+e^- case simply. We choose the mass of dark matter: 1, 10, 20, 40, 60, 80, 100, 200, 400, 600, 800, 1000 GeV and get the corresponding 2σ value of f_{UCMHs} respectively. The results are shown in Tab. 1 and Fig. 4. From these we can see that for the larger dark matter mass, the allowed

$M_\chi(GeV)$	f_{UCMHs}	$M_\chi(GeV)$	f_{UCMHs}	$M_\chi(GeV)$	f_{UCMHs}
1	0.22×10^{-4}	60	0.11×10^{-2}	400	0.69×10^{-2}
10	0.15×10^{-3}	80	0.16×10^{-2}	600	0.12×10^{-1}
20	0.38×10^{-3}	100	0.23×10^{-2}	800	0.13×10^{-1}
40	0.72×10^{-3}	200	0.32×10^{-2}	1000	0.16×10^{-1}

Table 1. Posterior constraints on the current fraction of UCMHs formed during e^+e^- for the different dark matter mass, where the 2σ values are shown.

value of f_{UCMHS} becomes larger gradually. The similar discussion and same method are also present in [5], where the authors change the mass of dark matter for MCMC method and get the constraints on the UCMHs. The results are consistent between of them. On the other hand, for the constrains on f_{UCMHs} from CMB, the main contribution comes from the recombination [6]. During the reionization period, the standard sources such as stars or active galactic nuclei (AGN) are dominant. So the including of common dark matter halos is not so important, this is shown in [6], where the authors only consider the contribution from UCMHs and find the comparable results. As we have mentioned above, we have assumed that the energy released by dark matter annihilation is all deposited in the medium. It is not always the truth. For example, the neutrino can take the energy off without any effect on the medium. In the higher redshift, $z \sim 1000$, the fraction is about $30\% \sim 40\%$. It will decrease to $\sim 1\%$ in the lower redshift $z \sim 6$ [35]. So if one consider these effect, the final results can be different for the different annihilation channels and productions [18, 36]. [1]

As we have shown in section II, the extragalactic γ-ray flux from UCMHs formed during e^+e^- phase transition would exceed the $Fermi$ observations for some parameters. In order to be consistent with $Fermi$ data, we get the 2σ conservative limitations of the current abundance of UCMHs using these data following the method in [37]:

$$\phi_i^\gamma \leq M_i + n \times \Sigma_i \qquad (3.5)$$

where ϕ_i^γ is the integrated flux from our model in ith eneregy bin corresponding to the measured flux, M_i. Σ_i is the error of ith bin. $n = 1.28$ and 1.64 correspond to the 90% and 95% confidence level.

The results are shown in Fig. 4 where we have shown the $\tau^+\tau^-$, $b\bar{b}$ channels. We can see that the constraints for the $b\bar{b}$ channel are more stringent than those for the $\tau^+\tau^-$ channel especially for larger dark matter mass. Moreover, comparing with the results obtained from CMB, the constraints from $Fermi$ are much better. So the observations of extragalactic γ-ray background can give more stringent constraints on the current abundance of UCMHs than the CMB data. In Fig. 4, we also show the constraints including the contributions of halos. [2] From the results we can see that the constraints are same nearly for with and

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[1]Actually in our work, from Eq.(3.1) nad (3.3), we can also think that the two parameters used by us is the combination of f and other parameters: $f f_{UCMHs}$ and $f^{-1}M_\chi$. So the final results are the constraints of them. For the different f we can get the corresponding constraints on f_{UCMHs} and M_χ. Of course, in this case, we also treat f as a constant instead of a function of redshift.

[2]In this paper, we do not include the contributions from the standard astrophysical sources. If these objects are also considered, then the allowed abundance of UCMHs would be more lower. We will consider these in the other papers.
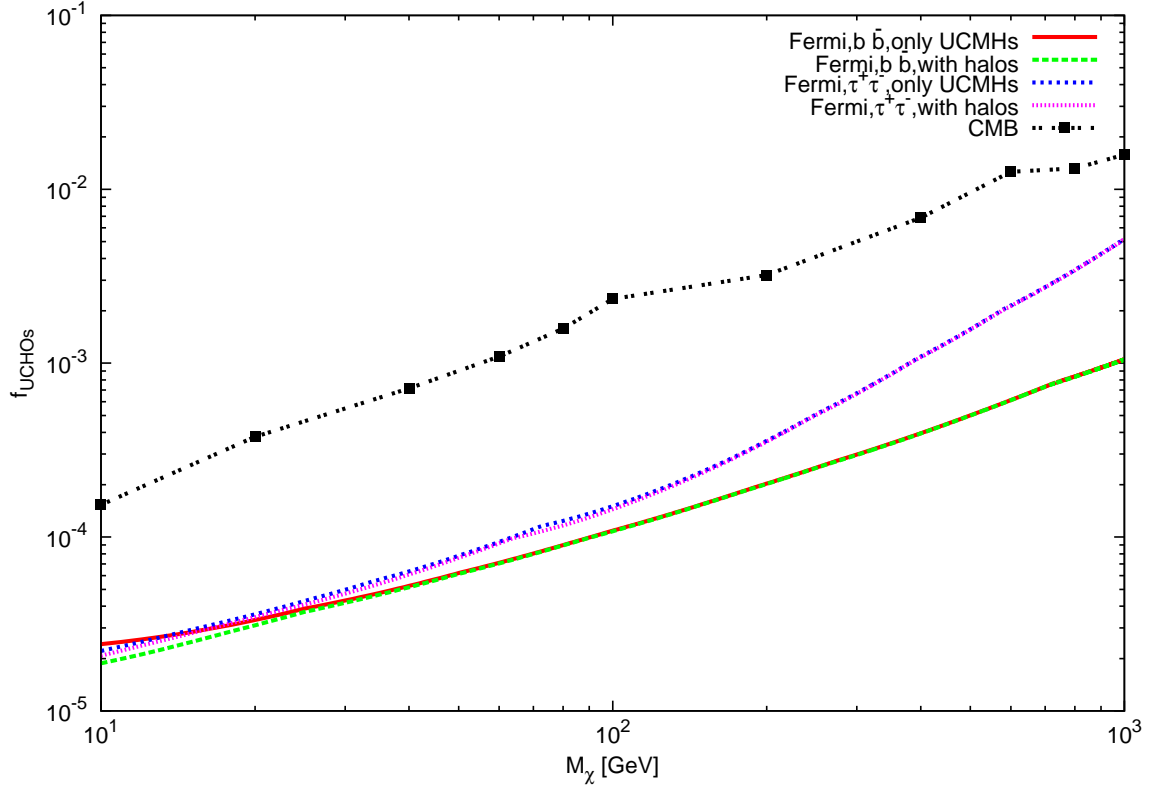
Figure 4. The constraints on the current abundance of UCMHs produced during e^+e^-: f_{UCMHs} from *Fermi* and CMB observations. The model and parameters used have been described in text. The constraints using the CMB data are obtained from Tab. 1.

without halos. There are some light differences for the $b\bar{b}$ channel in the lower dark matter mass $M_\chi \lesssim 30\text{GeV}$.

4 Conclusion

We have investigated the extragalactic γ-ray background from a new class of dark matter structure named UCMHs and gotten the constraints on the current abundance of them using the *Fermi* observations. On the other hand, because the dark matter annihilation within the UCMHs has effect on the evolution of cosmological ionization fraction, we also use the CMB data to get the constraints on the fraction of UCMHs. In our paper, we only show the constraints on the UCMHs formed during e^+e^- due to the same contributions of UCMHs produced during EW and QCD.

From the results, we find that the constraints are weaker for CMB data than *Fermi* data. About the dark matter mass $M_\chi \sim 10GeV$, the current fractions of UCMHs are about $\sim 10^{-5}$ and $\sim 10^{-4}$ respectively corresponding to *Fermi* and CMB data. For the *Fermi* observations, we have calculated two channels: $\tau^+\tau^-$ and $b\bar{b}$. We find that for lower mass of dark matter $M_\chi \lesssim 100GeV$, the constraints are comparable, while for larger one the constraints from $b\bar{b}$ channel are more stringent. If we consider the contributions from the halos and subhalos, the results are not changed nearly especially for larger dark matter mass $M_\chi \gtrsim 100GeV$.

For this new dark matter structures, it is hope that other present or the future observations can have the power to give new constraints on them. For the recent observations of positron, such as PAMELA [38], Fermi [39] and ATIC [40], may be the signal from the dark matter annihilation (for a review one can see [41]). The characteristic of UCMHs would explain these observations. On the other hand, the extra energy injection into the medium can also have effect on the 21cm signals. So we expect that this future observations can also give the new and stronger constraints on the UCMHs.

Moreover, the constraints on the abundance of UCMHs can be translated into constraints on the primordial curvature perturbation [42]. We will consider them in the near future.

Acknowledgments

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